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RESPONSE OF SANDHILL CRANE (*GRUS CANADENSIS*) RIVERINE ROOSTING HABITAT TO CHANGES IN STAGE AND SANDBAR MORPHOLOGY†

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ABSTRACT

Over the past century, flow regulation and vegetation encroachment have reduced active channel widths along the central Platte River, Nebraska. During the last two decades, an annual program of in-channel vegetation management has been implemented to stabilize or expand active channel widths. Vegetation management practices are intended to enhance riverine habitats which include nocturnal roosting habitat for sandhill cranes. Evaluating the success of other management treatments such as streamflow modification requires an understanding of how flow shapes the sandbars in the river and how sandbar morphology interacts with flow to create crane habitat. These linkages were investigated along a 1-km managed river reach by comparing the spatial pattern of riverine roosts and emergent sandbars identified with aerial infrared imagery to variables computed with a two-dimensional hydraulic model. Nocturnal observations made multiple years showed that the area and patterns of riverine roosts and emergent sandbars and the densities of cranes within roosts changed with stage. Despite sandbar vegetation management, low flows were concentrated into incised channels rather than spread out over broad sandbars. The flow model was used to compute hydraulic variables for identical streamflows through two sandbar morphologies; one following a period of relatively high flow and the other following the low-flow period. Compared with the simulation using the morphology from the antecedent high flow, the simulation using the morphology from the antecedent low flow produced a smaller quantity of available wetted area. These remote-sensing observations and hydraulic simulations illustrate the importance of considering flow history when designing streamflows to manage in-channel habitat for cranes. Published in 2008 by John Wiley & Sons, Ltd.

KEY WORDS: ecohydraulics; habitat assessment; hydrodynamic modelling; instream flow; Platte River; sandhill cranes

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INTRODUCTION

Approximately 450 000–550 000 sandhill cranes (*Grus canadensis*) migrate every spring through the central Platte River valley in Nebraska (Kinzel *et al*., 2006). This region is an important staging site for sandhill cranes as they amass fat reserves to aid in travelling from their wintering grounds in Texas and Mexico to their breeding grounds in Canada, Alaska and Siberia (Krapu *et al*., 1985). Waste corn available on agricultural lands adjacent to the Platte River satisfies crane energy and fat storage requirements and invertebrates consumed in grasslands and wet meadows adjacent to the river channel provide for protein and calcium needs (Reinecke and Krapu, 1986). The quantity and quality of grasslands and wet meadow habitats along the central Platte River have declined as many of these areas have been drained, levelled and converted to cropland (Krapu *et al*., 1982; Sidle *et al*., 1989).

The central Platte River functions as nocturnal roosting habitat for sandhill cranes (Krapu *et al*., 1984). The river has undergone a dramatic morphologic transformation over the last century. The changes in river planform have been illustrated by comparison of serial aerial photography (Williams, 1978; Eschner *et al*., 1983; Johnson, 1997). A variety of interrelated influences including alterations in streamflow, vegetation patterns, sediment supply and bridge constrictions are typically cited as responsible for causing the wide, braided, sand channels of the Platte River to narrow and channelize. In the past, most attention was directed to the reduction in peak flows caused by upstream flow regulation (Williams, 1978; Eschner *et al*., 1983). As both the magnitude and frequency of flows capable of scouring newly formed vegetation on sandbars were reduced, vegetation colonized these surfaces and

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the root structure provided increased resistance to erosion. During periods of inundation, sediment was deposited on vegetated sandbars causing them to aggrade vertically due to deceleration of the flow from increased drag on the bars. Over time, as side channels became filled and/or the course of the river was redirected, vegetated sandbars also accreted laterally to the floodplain, narrowing the active river channel. Recently some focus has also been given to the change in the sediment inputs to the central Platte River due to flow regulation. Reduction in the supply of upstream sediment is believed to have stimulated the winnowing of fine-grained material from the riverbed leaving coarser bed-sediments (Kinzel *et al*., 1999). Changes in bed elevation in transects measured along the central Platte River since 1989 also suggests imbalances in the sediment budget (Murphy and Randle, 2001).

The spatial distribution of sandhill cranes along the central Platte River has been associated with changes in river morphology (Krapu *et al*., 1982; Faanes and LeValley, 1993). Faanes and LeValley (1993) demonstrated that from 1957 to 1989 the distribution of staging sandhill cranes shifted in the central Platte River, decreasing along river reaches where woody vegetation encroachment and channel narrowing have been the greatest and increasing along reaches that have remained relatively wide and unvegetated. The US Fish and Wildlife Service believe the historical loss of in-channel roosting habitat for cranes due to channel narrowing was confining cranes into fewer available areas of the river resulting in high roosting densities (US Fish and Wildlife Service, 1981).

A concentrated roosting population is believed to have the potential to negatively influence the health of the migrating crane population for at least two reasons. Krapu *et al*. (1982) expressed concern that if cranes were to seek alternative roosting sites they might do so south of the Platte River in the Rainwater Basin, an area where avian cholera outbreaks in waterfowl were previously documented. The high concentration of cranes in central Nebraska in spring also increases the chances that severe localized weather events could directly impact a large percentage of the staging population, possibly causing high mortality. In addition to these concerns, recent radio telemetry data suggest that as streamflows have declined in recent years in the central Platte River valley, fidelity of cranes to roost sites and fat storage by cranes have also declined (G. Krapu, US Geological Survey (USGS), unpublished data). If this trend continues these findings may have implications to the health of the migrating population if crane capacity to store fat is adversely affected.

Over the last few decades, active channel width has been artificially maintained and vegetation growth on sandbars has been mitigated by the efforts of environmental organizations on their properties and on private lands through the US Fish and Wildlife Service's Partners for Wildlife Program. These groups currently manage in-channel vegetation along approximately 30 km of river channel in the central Platte River each fall, principally through the use of heavy machinery. A specialized piece of equipment called a Clearway is first used to cut the stems of woody vegetation up to 20 cm in diameter. Once the woody vegetation is removed, Clearway activities are followed by the application of herbicides and/or discing, which involves using a tractor to roll a row of steel discs over the cleared area to destroy the underlying root system of herbaceous and seedling vegetation. Johnson (1997, 2000) questioned the merit of these large-scale vegetation management activities and believed they had the potential to increase sediment loads locally and could be responsible for downstream deposition and channel narrowing. Clearing along the Platte River has also been criticized because this practice is believed to promote the spread of weeds including the invasive purple loosestrife (Johnson and Boettcher, 1999).

Concern that the reduction of available in-channel habitats has been detrimental to the whooping crane, listed as endangered in 1967 (US Fish and Wildlife Service, 1967), has prompted interest in identifying relations between streamflow and habitat quality for cranes. Whooping cranes use the Platte River as a stopover point during their spring and fall migration while sandhill cranes, for which the central Platte River valley functions as a staging area, stay for a longer time interval in the spring. However, both species share similar indices for roosting habitat such as unobstructed view, wetted channel width and shallow water depths. The model being used to assess whooping crane roosting habitat (C4R) (Carlson, 1994) is coupled to a one-dimensional hydraulic model, Physical Habitat Simulation system (PHABSIM) (Bovee and Milhous, 1978). PHABSIM is used to simulate river flows and predict roosting habitat variables including depth and unobstructed width over a range of river flows. The models are used as a management tool to determine the streamflows required in channel cross sections that optimize the quality of roosting habitat for whooping cranes along the central Platte River (Farmer *et al*., 2005).

Understanding the response of sandbars and in-channel habitats to managed flow events requires a modelling approach that can predict the complex spatial and temporal evolution of channel morphology. One-dimensional models do not capture the spatial accelerations in the flow and streamline curvature that, when coupled with

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sediment transport, produce sandbar shape, persistence and evolution. One-dimensional habitat models may assume the channel morphology is static or treat variability in cross-sectional shape only in a stochastic sense. They also do not represent the spatial distribution of depths and velocities that determine roosting habitat patches. While these approaches may have utility, they do not provide physically based insight into the fluvial process that shapes the channel and affects the habitat. Therefore the goal of the study described in this paper was to develop an understanding of how river stage and sandbar morphology influence habitat for roosting cranes.

The specific objectives of the research described in this paper were to: (1) determine the range in hydraulic variables (depth and velocity) that constitute available riverine roosting habitat for sandhill cranes by relating observations of roosting cranes to predictions of depth and velocity computed with a two-dimensional flow model and (2) use the model predicted variables along with direct observations of roosting cranes to assess how the availability of riverine roosting habitat relates to the total roost area used over multiple river stages and sandbar morphologies. This paper also sets the stage for future work directed towards the multi-dimensional modelling of flow, sediment transport and sandbar response and the linkage of these processes to in-channel habitat creation and maintenance.

MATERIALS AND METHODS

Study area

A 1-km reach of the central Platte River located within the National Audubon Society's Lillian Annette Rowe Sanctuary, hereinafter referred to as Rowe Sanctuary, was selected to examine the influence of river stage and sandbar morphology on the areal extent and spatial distribution pattern of sandhill crane riverine roost sites (Figure 1). Riparian and island vegetation within the Rowe Sanctuary is managed each fall to preserve wide, unobstructed views for cranes. The Rowe Sanctuary site is located along a relatively wide section of the central Platte River (200–250 m) and is also in close proximity to crane feeding and loafing habitats in adjacent cornfields and wet meadows. From dusk until dawn tens of thousands of cranes can be observed roosting or standing on submerged sandbars along this reach. These riverine roosts offer cranes protection from nocturnal predation. The Rowe Sanctuary is within a 9-km river reach where almost 20% of the sandhill cranes roosting in the central Platte River have been observed (Kinzel *et al*., 2006) and approximately 40% of the historical sightings of whooping cranes in the central Platte River have been documented (Farmer *et al*., 2005).

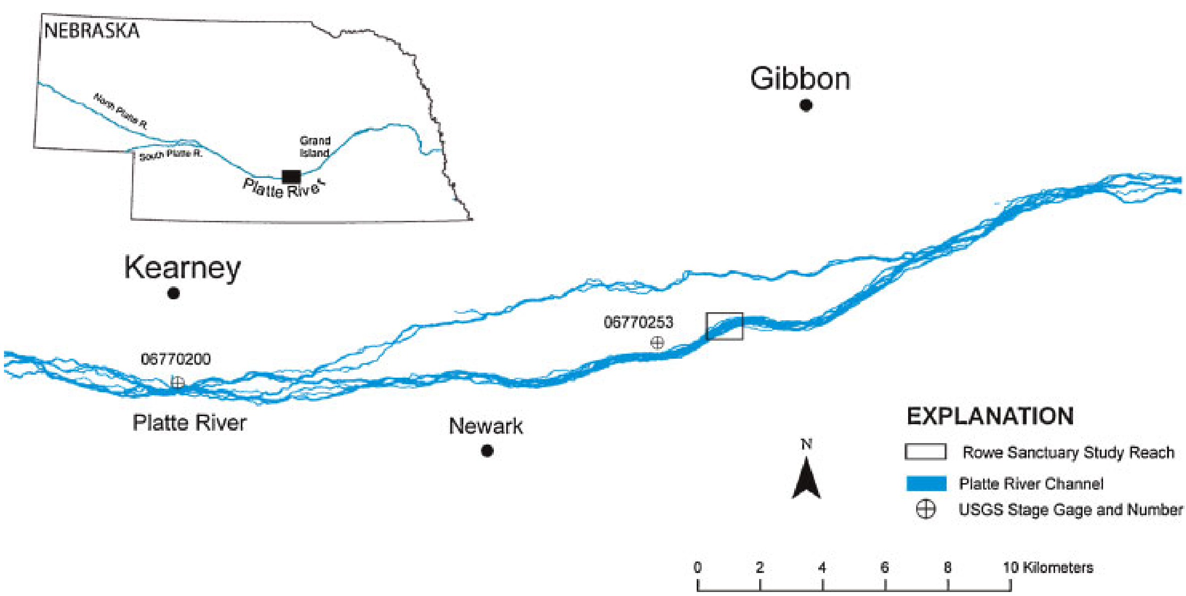

Figure 1. Map of a section of the central Platte River showing the location of the study reach. This figure is available in colour online at www.interscience.wiley.com/journal/rra

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Hydrology

Streamflow information was obtained from a stage-discharge relation developed at the USGS streamflow-gaging station 06770200, Platte River near Kearney, Nebraska, located 17.5 km upstream from the study site (Figures 1 and 2A). The USGS streamflow-gaging station at Kearney has been operated since 1982 and measures the total flow in the river. The largest annual peak discharge measured for the period of record occurred on 29 June 1983 ($671\,m^3s^{-1}$). Measurements of river stage were collected at a USGS continuous recording stage gage, 06770253 Platte River near Newark, Nebraska (Figure 2B). This gage was installed in April 1999 and is located along the south channel of the Platte River 2.5 km upstream from the study site (Figure 1).

The river branches into two distinct channels approximately 0.8 km below the streamflow-gaging station at Kearney. The percentage of flow carried in the south-branching channel, which passes through the Rowe Sanctuary study site, was determined by Ziewitz (1988) to be approximately 68% of the total flow. A value of 65% was used in this study because it fell within a range of more recent comparisons of the flow at Kearney to discharge measurements made by the USGS in the south channel in 1994 and 1995 and measurements made near the Newark stage gage in March of 2002 and 2005.

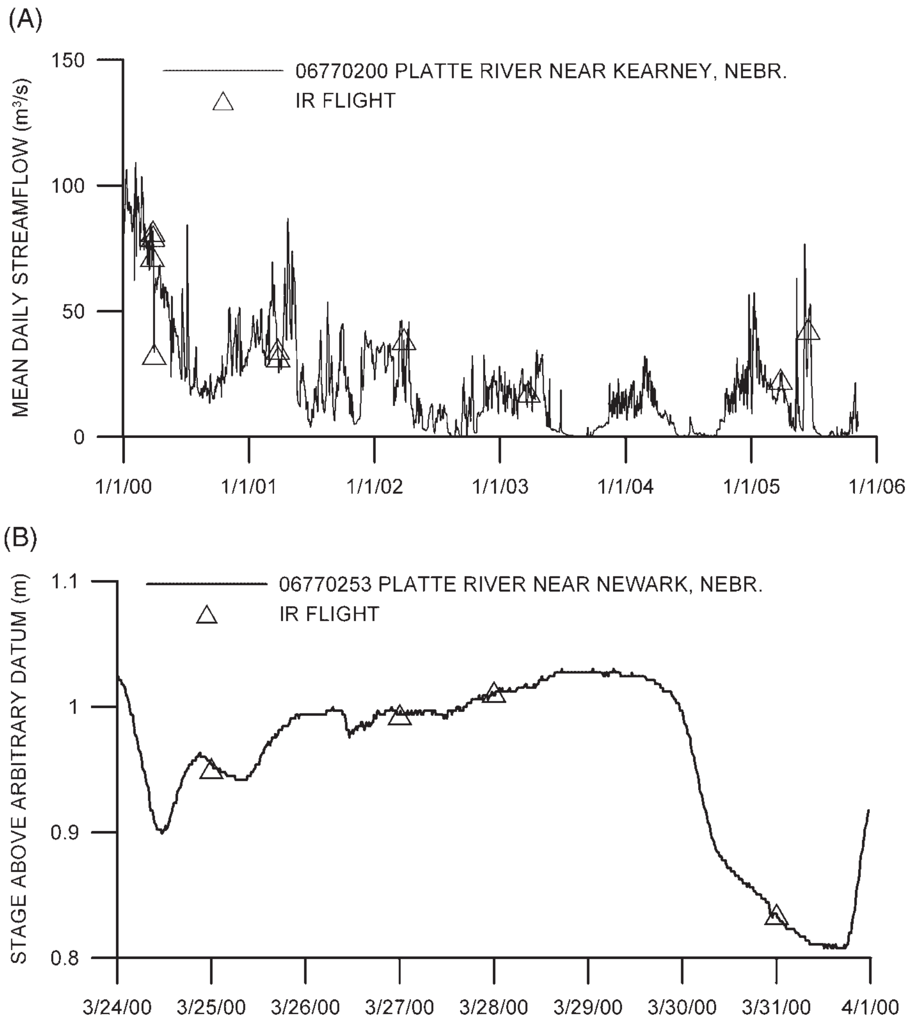

Figure 2. (A) Graph showing the hydrograph for USGS streamflow-gaging station 06770200, Platte River near Kearney, Nebraska during the study. Dates when infrared imagery was collected are shown with triangles. (B) Graph showing the river stage at USGS 06770253, Platte River near Newark, Nebraska from 24 March 2000 to 1 April 2000. Dates when infrared imagery was collected are shown with triangles

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Remote sensing

Because cranes often arrive at the river after sunset and begin to depart before sunrise, traditional aerial photography was not sufficient to capture the entire population and distribution of roosting cranes. For this reason, a private contractor was employed to collect images of the nocturnal roosts with an aerial thermal-infrared video system. The video system included a Mitsubishi IR-M600 infrared camera mounted vertically over a hole in the bottom of a Cessna 182 fuselage. The camera detected infrared radiation in the 3–5 μm wavelength. The video imagery was recorded directly on digital video tapes. In the thermal infrared images, sandhill cranes appeared colder than the water they were standing in because their feathers insulated their body heat. Because the temperature of the surface of sandhill crane feathers was close to the ambient air temperature, the difference in the thermal emissivity between the water and feathers provided a contrast that was detectable in the infrared imagery. Emergent sandbars also were easily resolved in the imagery because of their temperature contrast with the surrounding water. The authors have used this infrared-video technology to estimate the population size of sandhill cranes in the central Platte River valley (Kinzel *et al*., 2006) and as a technique to delineate emergent sandbar habitats (Heckman *et al*., 2006).

Each year (2000 through 2003 and in 2005) thermal videography was collected along the central Platte River for a maximum of five nights on and around the fourth Tuesday of March. This time period was selected to coincide with the anticipated peak of the migrating sandhill crane population (Benning and Johnson, 1987). However, in any given year, weather conditions ultimately determined the number of nights imagery was collected. For this reason, imagery was acquired during five nights in 2000, and two nights in 2001, 2002, 2003 and 2005. The thermography was acquired between 2300 and 0400 hr to ensure a high percentage of cranes had returned to the river to roost. Because of the tradeoff between resolution and field of view of the infrared camera, the aircraft was flown at two altitudes. A high altitude (approximately 1200 m above ground level) provided sufficient field of view to capture the entire width of the river channel and permitted georectification of the imagery. Individual sandhill cranes could not be resolved at this altitude, as the resolution of a single pixel in this imagery was approximately 0.25 m^2. However, because of the close proximity of cranes to one another on the river, it was possible to resolve contiguous areas of crane presence or roosting sites in this imagery. Lower altitude flights (approximately 300 m above ground level) were capable of resolving individual cranes but because of the smaller field of view these images were difficult to georeference over the open river channel. In addition ensuring complete coverage of the entire width of river at this altitude was logistically difficult and increased the potential of disturbing the cranes. The lens parameters of the infrared camera and the altitude were used to determine the field of view and estimate the spatial density of cranes in their roosts for the low altitude images (Kinzel *et al*., 2006). The imagery from the low altitude flights indicated that an individual crane generally occupied less than 2.5 m^2 of roost area.

The video from the high altitude flights was later reviewed and processed using a digital video player to stream the video into a desktop computer through an IEEE 1394 connection. Individual video frames were selected and captured using a software package for digital video editing. The video images were imported into a geographic information system (GIS) and registered using 1: 24 000-scale orthophotographs. Easily identifiable feature analogues, such as trees or island points, were used in the registration process to scale and rotate the video images. This technique permitted individual video images from the nights the study reach was flown to be placed side by side ensuring complete coverage of the reach. The outlines of the roost sites and exposed sandbars were then delineated and digitized from the images within the GIS to create a digital coverage of correctly sized and oriented roosts and sandbars (Figures 3 and 4). The GIS software was also used to compute the areas of these polygons.

On 15 June 2005 aerial colour near-infrared imagery was collected along the Rowe Sanctuary reach coincident with an experimental airborne laser altimetry survey (Kinzel *et al*., 2007). These images were collected at a discharge of approximately 38 $m^3 s^{-1}$ at the Kearney streamflow-gaging station and a water-surface elevation of approximately 0.85 m at the Newark stage gage. It was possible in this imagery, based on the spectral reflectance, to delineate vegetated sandbar areas (red) from areas where water was present in the channel (blue). Ground surveys and ground photography taken at the time this imagery was collected showed that the vegetated areas in this imagery closely corresponded to uninundated sandbar areas. The colour-infrared imagery was georeferenced to orthophotographs using the procedure described above.

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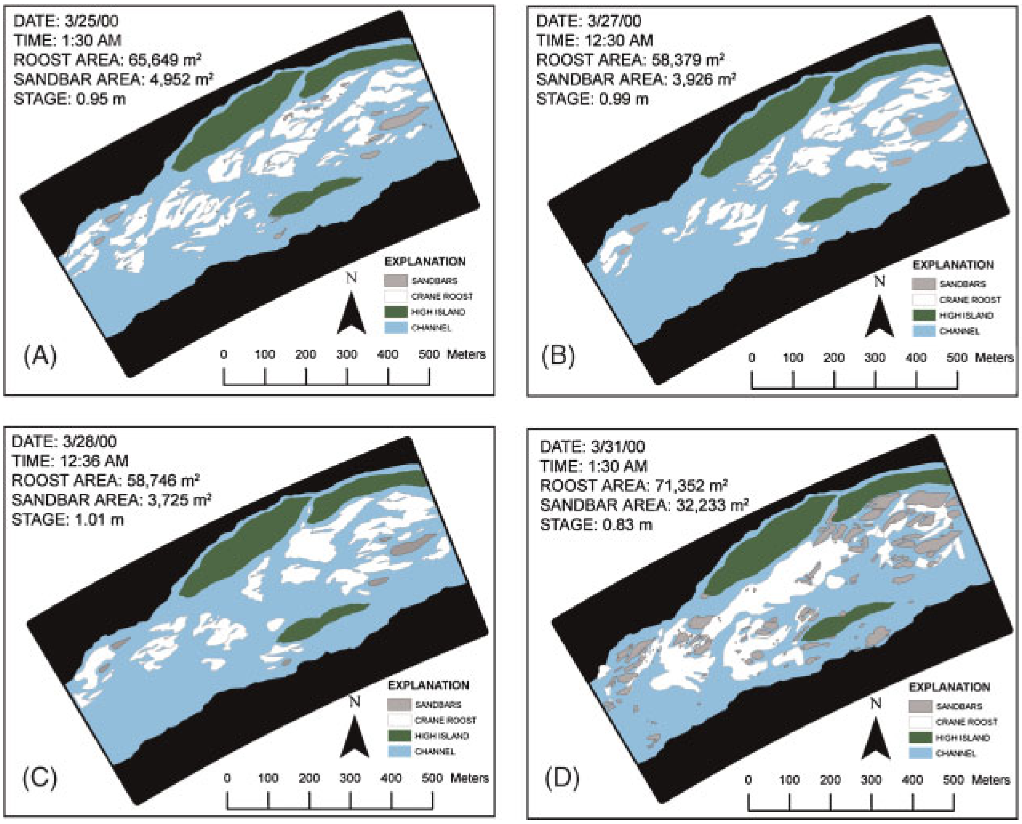

Figure 3. Area and spatial distribution of riverine roosts and exposed sandbars in the Rowe Sanctuary for imagery collected over various nights and river stages in 2000. Stage was recorded at the Newark gage and is referenced to an arbitrary datum.

Channel surveys

Each year during late March the in-channel topography in the Rowe Sanctuary study reach was comprehensively surveyed. This period of time was chosen to coincide with the spring migration season and the aerial infrared imaging. Twenty-two cross sections were established and oriented perpendicular to the centreline of the study reach. A survey-grade global positioning system with multiple roving units was used to precisely navigate along the cross sections and compute the elevation along these lines. Topographic surveys were made relative to the North American Datum of 1983 (NAD83) and the North American Vertical Datum of 1988 (NAVD 88). Profiles following the channel and river bank and island topographic points were also surveyed through the reach. Additional topographic data from the airborne laser altimetry surveys described above supplemented the elevation data collected on the high islands and river banks.

Hydraulic modelling

The topographic survey data were used as input to the USGS Multi-dimensional Surface Water Modelling System (MD_SWMS) (McDonald *et al*., 2005). MD_SWMS is a graphical user interface that is used as a pre- and post-processing application for hydraulic models developed by the USGS. A channel-fitted, curvilinear orthogonal coordinate grid was created in MD_SWMS by interactively digitizing a centreline through the model reach. The dimensions of the numerical grid cells used in the hydraulic simulations were approximately 5×5 m. The survey data were mapped and interpolated onto the numerical grid using a search template. The length and width of the search template were defined to be 30 m in the streamwise direction and 5 m in the cross-stream direction. The grid

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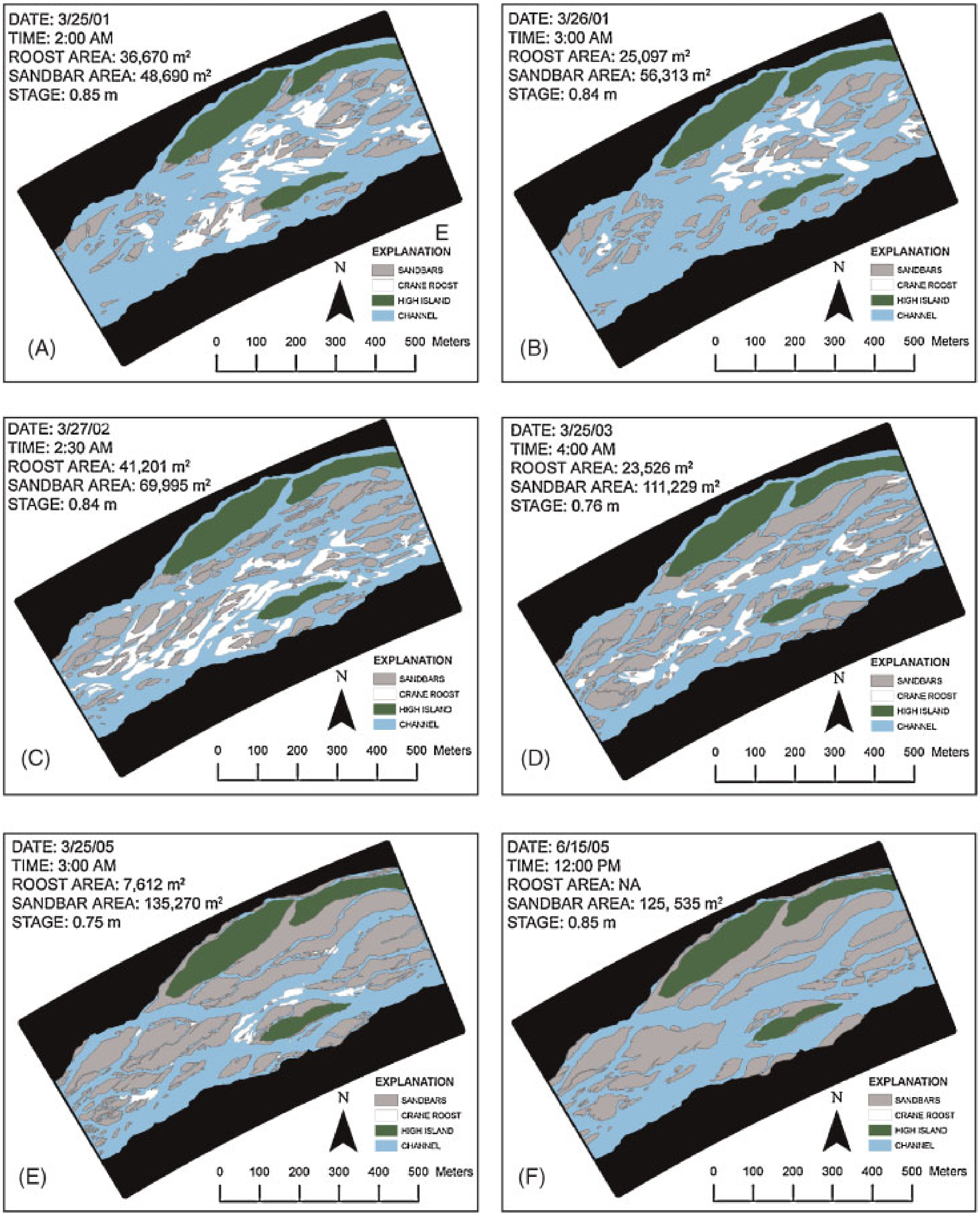

Figure 4. Area and spatial distribution of riverine roosts and exposed sandbars in the Rowe Sanctuary for imagery collected in 2001, 2002, 2003 and 2005. Stage was recorded at the Newark gage and is referenced to an arbitrary datum. Figure F was not collected during the crane migration season.

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space was searched for one or more surveyed points that fell within the specified dimensions. If points were found in the template, the numerical cell was given the inverse distance weighted average elevation of the points. If a point was not found in the template the template size was doubled in size and the process repeated until at least one point was located. This process continued until each grid cell was assigned an elevation value (Figure 5).

MD_SWMS was used to run a depth-averaged two-dimensional flow model: Flow and Sediment Transport and Morphological Evolution of CHannels (FaSTMECH) (McDonald *et al*., 2005). The FaSTMECH model solves the Reynolds-averaged momentum equations at each grid node using an explicit finite-difference scheme and uses an implicit-finite difference scheme to update the water-surface elevations. An operator splitting and upward-differencing technique is used for the momentum equations for stability and the water-surface elevations are determined using a Semi-Implicit Method for Pressure Linked Equations (SIMPLE) (Patankar, 1980). The numerical model iterated until the mass and momentum equations were solved at each node. Iterative wetting and drying of grid nodes was permitted by the model. Relaxation coefficients were assigned to enable convergence of the model. Two boundary conditions were needed for a flow solution, a downstream water-surface elevation that was determined from either a recording pressure transducer or with a direct measurement at the time of the topographic survey, and a discharge that was calculated from the proportion of the discharge from the upstream USGS streamflow-gaging station 06770200, Platte River near Kearney, Nebraska (see Figure 1). The model was calibrated by adjusting a single-value drag coefficient parameter until the predicted and measured water-surface elevations were in good agreement.

MD_SWMS was used to generate an ASCII export file that included the horizontal coordinates of each grid node, the depth and the velocity magnitude computed by the FaSTMECH model. The export file was then used to create a spatial coverage of grid node locations in the GIS. This methodology allowed output from the model to be easily compared and overlain on the remotely sensed data.

RESULTS

Remote sensing—2000 roosts and sandbars

The distribution patterns of roost sites and exposed sandbars for four of the five nights imaged during the 2000 migration season are shown (Figure 3). The area of the roosts and sandbars and the river stage are also given for each night of imagery. The 2000 roost patterns were influenced by the flow and corresponding stage in the river channel (Figure 2B). On 25 March, at a stage of 0.95 m, cranes roosted on the submerged sandbars in the study reach (Figure 3A). As discharge and stage increased on 27 March, the area of exposed sandbars and roosts decreased (Figure 3B) possibly because cranes were forced to use higher elevations on the submerged bars. The roost areas and crane distributions are similar as are the sandbar areas for the nights of 27 and 28 March when the stages were somewhat similar (Figure 3B,C). During 31 March, the effects due to an upstream water diversion were observed (Figure 2B). As the stage decreased from that in the previous nights, the distribution pattern changed from many isolated roosts to fewer, more contiguous roosts (Figure 3D). The total roost area digitized in the reach was also greater for this stage than for any of the other nights of imagery.

Sandbars in the Rowe Sanctuary were also influenced by the streamflows prior to our topographic and aerial infrared surveys. This antecedent period of relatively high discharge in 2000 (Figure 2A) formed large, lobate sandbars through the study reach. In the image from 31 March 2000 (Figure 3D) the stage was the lowest and consequently the exposed sandbar area was the greatest of all the nights in 2000. Despite this low stage, a large portion of the channel area in this image, especially towards the centre of the channel where the cranes were roosting, was covered with water.

Remote sensing—roosts and sandbars imaged in subsequent years

The distribution patterns of roosts and exposed sandbars for nights imaged in the 2001, 2002, 2003 and 2005 migration seasons are shown in Figure 4. Poorer weather conditions during these years restricted thermal imaging to fewer nights than in 2000. More riverine roost area was imaged in the study reach for the nights surveyed in 2000 than was imaged in 2001 (Figures 3 and 4A,B). Also, in 2001, the areas of the exposed sandbars in the reach were

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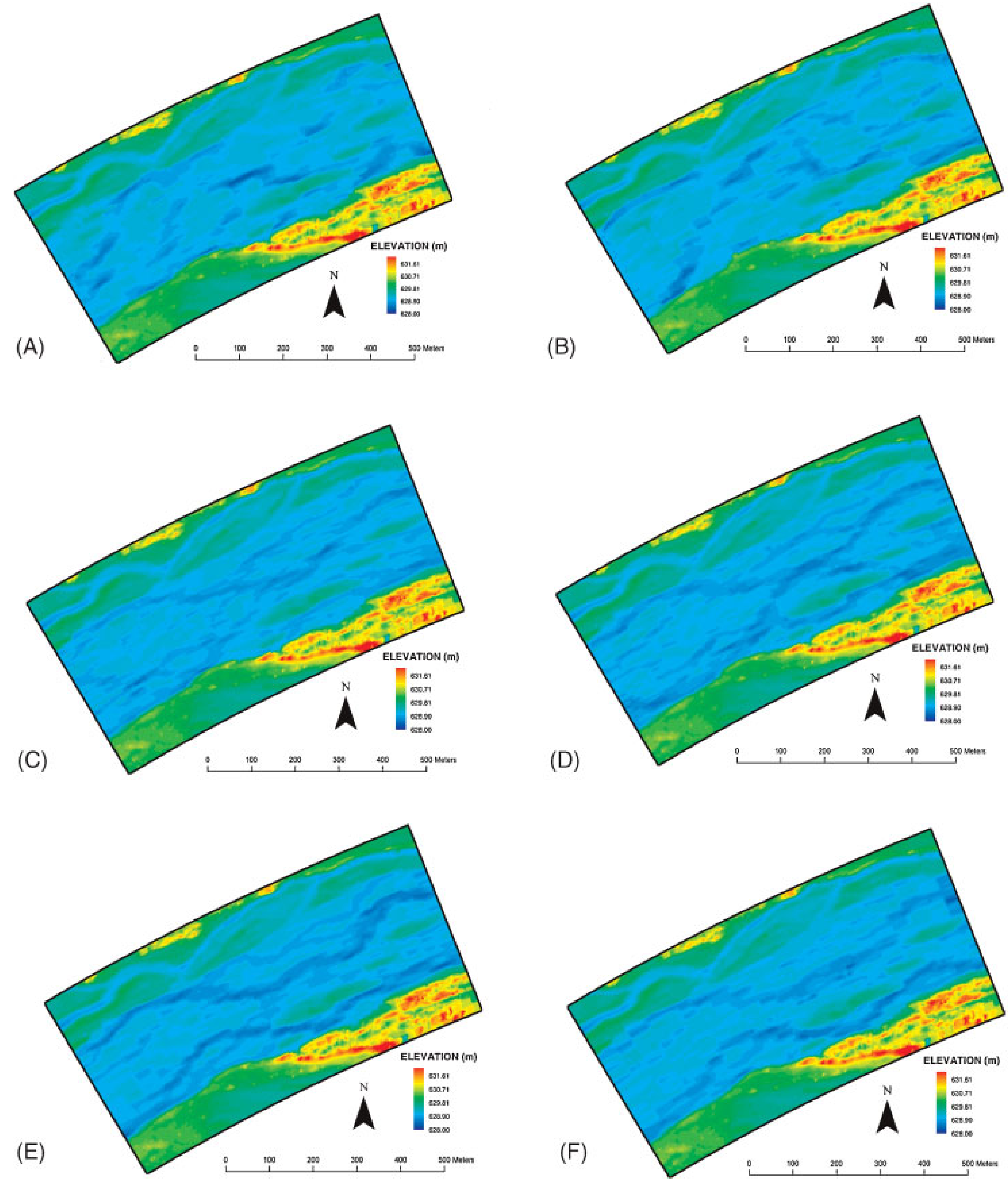

Figure 5. Maps of detrended river channel topography in the Rowe Sanctuary for surveys collected in March 2000 (A), 2001 (B), 2002 (C), 2003 (D), 2005 (E) and May 2005 (F).

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greater than that imaged on 31 March 2000 despite the fact that the river stage when these images were collected was higher (Figures 3D and 4A,B). The stage was the same on 27 March 2002 (Figure 4C) and at the time the image from 26 March 2001 was collected (Figure 4B), but exposed sandbar areas were larger in March 2002 than they were in March 2001. While the stage was 1 cm higher on 27 March 2002 (Figure 4C) relative to that observed on 31 March 2000 (Figure 3D), the area of exposed sandbar digitized was twice as large. The images collected in 2003 and in 2005 (Figure 4D,E) further illustrate the effect of a period of prolonged low flows (Figure 2A) had on the sandbars in the channel and on the distribution of roosting cranes. While mechanical discing each fall prevented perennial vegetation like cottonwood (*Populus ssp.)* and willow (*Salix ssp*) from becoming established on the sandbars, at these lower stages the flow became concentrated into narrower and deeper channels through the reach. The image from 25 March 2003 was collected at a stage lower than the imagery collected in the previous years resulting not only in a greater area of exposed sandbars but also the attachment of these bars to the high islands along the north bank. On 27 March 2005 (Figure 4E) the stage was 1 cm lower than that on 25 March 2003 (Figure 4D) consequently the exposed sandbar area was greatest of all nights imaged. The exposed bars were more contiguous in this image as more of the flow was directed into the incised channels. The riverine roost area detected in the thermal-infrared imagery also declined from 2003 to 2005 and this is not particularly surprising because the wetted channel area had also diminished. The cranes that were roosting in the water in the 2003 and 2005 images are doing so in the centre of the channel as opposed to those seen in the 2000 images (Figure 3) which were observed closer to the river banks.

The colour infrared imagery obtained after the crane migration season, 15 June 2005, was registered (Figure 4F) and the area of the exposed sandbars was found to be only somewhat smaller, 125 535 versus 135 270 m^2, but in a similar configuration from that digitized using the thermography collected on 25 March 2005 (Figure 4E). However, the stage recorded on 25 March 2005 was 10 cm lower than that measured on 15 June 2005; and the 15 June 2005 stage was 2 cm greater than the stage measured on 31 March 2000 when the sandbar area was approximately one quarter as large. These observations were similar to those of Mosley (1982) who noted that increases in discharge in the braided Ohau River in New Zealand were accompanied by addition of faster, deeper water to a constant area of shallow, slow water. A layer of annual vegetation was also present on the sandbars in the Platte River at the time the colour infrared imagery was collected and provided the sandbars some resistance to erosion.

The sandbar areas and roost areas digitized from the thermal-infrared imagery were plotted as a function of the stages that were recorded at the time of the flights (Figure 6A,B). In Figure 6A, the thermal-infrared imagery collected in 2000 shows that most of the channel was inundated at stages greater than 0.95 m. As the stage declined to 0.83 m the quantity of exposed sandbar area increased. Subsequent measurements made in both 2001 and 2002 show that more sandbar area was digitized from the thermal-infrared imagery in the reach even though the stage at the time these images were collected was higher than 0.83 m. On 25 March 2001, the discharge measured upstream at Kearney was 28 m^3s^{-1} and in 2002 it was 36 m^3s^{-1}. The sandbar areas were the greatest at the lowest stages recorded on March 2003 and March 2005. In the final images collected, colour infrared photography flown on 15 June 2005, the exposed sandbar areas were four times as large as that determined on 31 March 2000. This was in spite of the fact that the discharge measured upstream at the Kearney gage, when accounted for the travel time to the Newark gage, was approximately 30 m^3s^{-1} on 31 March 2000 and 38 m^3s^{-1} on 15 June 2005.

A plot showing how the quantity of roost area changed as a function of stage is shown in Figure 6B. When the stage increased above 0.95 m in 2000, less roost area was observed and the maximum area was observed at a stage of 0.83 m on 31 March 2000. In later years with stages close to 0.83 m, much less in-channel roost area was observed than that observed on 31 March 2000. Lower stages in 2003 and 2005 also produced less in-channel roost area. One explanation for the apparent disjunction in the relation between sandbar area and stage, and between roost area and stage is the change in channel morphology that occurred throughout the study period.

The relationship between river stage and spatial density of cranes within their roosts was examined with low altitude imagery discussed previously. Five samples were collected during each night of low altitude observations in the Rowe Sanctuary reach. The mean and standard deviation of these measurements are shown in Figure 6C. While there is considerable variation, those measurements obtained during the lowest stage of 2000 show a smaller density of birds than the higher flows collected in 2000 or the lower stages observed in subsequent years.

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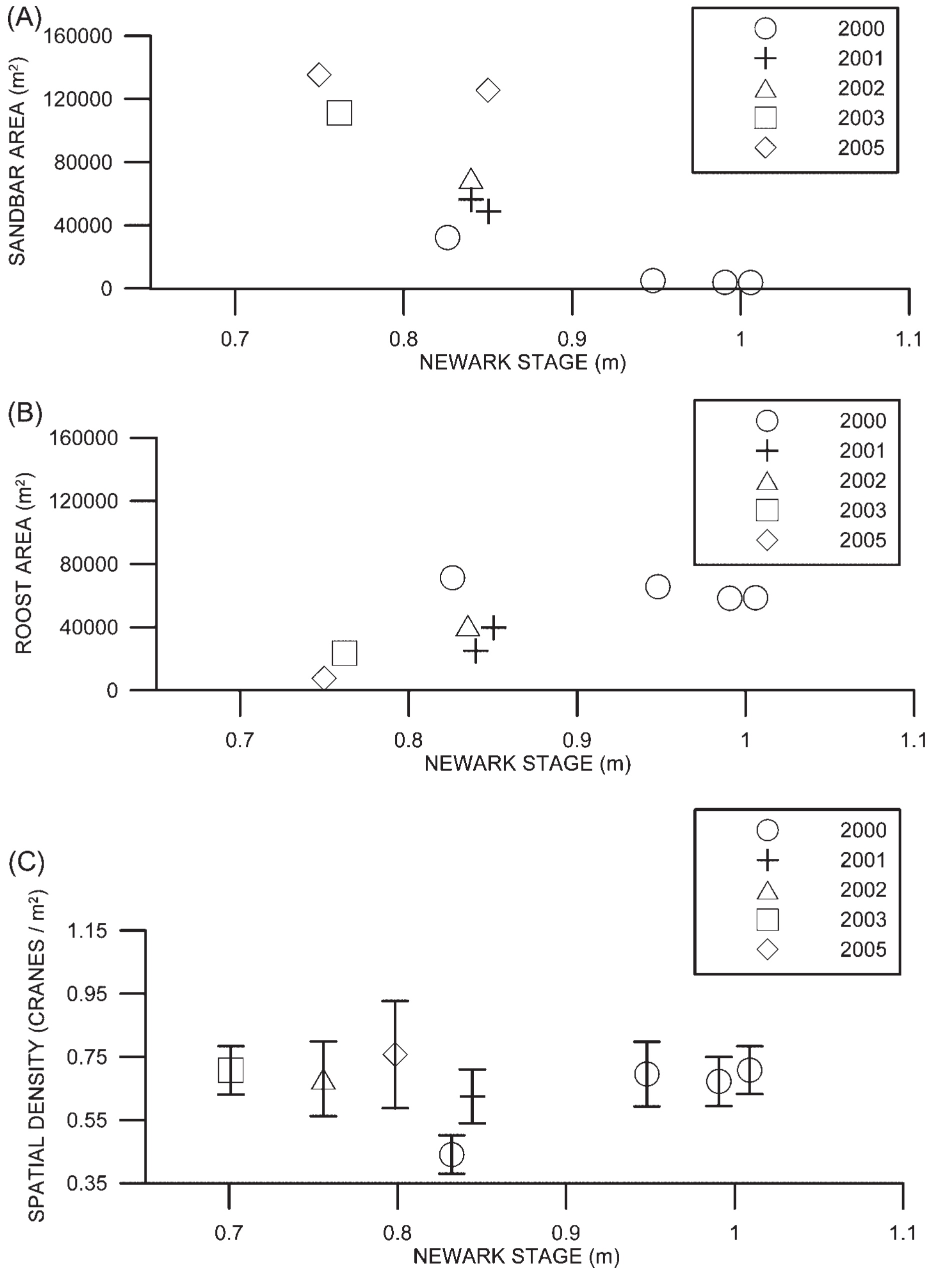

Figure 6. (A) Plot showing the relation between the sandbar area digitized and the stage recorded at the Newark gage. (B) Plot showing the relation between the roost area digitized and the stage recorded at the Newark gage. (C) Plot showing the relation between the spatial density of roosting cranes and the stage recorded at the Newark gage

Channel surveys

The surveyed elevations collected along the river cross sections in the Rowe Sanctuary were linearly interpolated at 1 m increments to generate a common number and position of data points for comparison among years. After exclusion of points collected along the high islands and on the river banks, the mean bed elevation was computed along each cross section and used to plot serial longitudinal profiles of the reach. For clarity only the elevations from the 2000, 2002 and 2005 surveys are shown (Figure 7A). Decreases in mean bed elevation from 2000 to 2005 occurred with greater frequency and with greater magnitude at the downstream end of the study site. In addition, the

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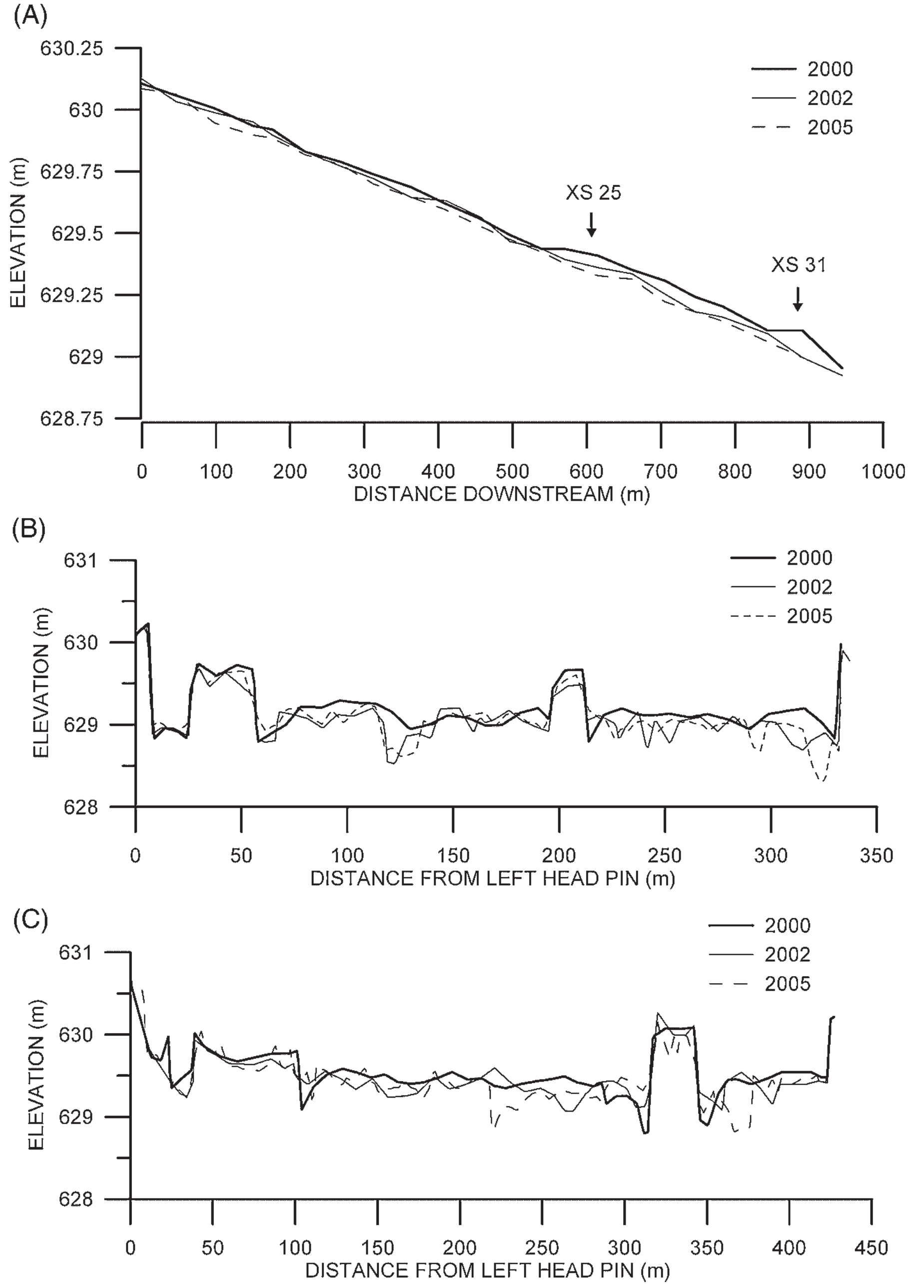

Figure 7. (A) Serial longitudinal profiles of the study reach. The locations of cross section 25 and 31 are shown with arrows. (B) Serial elevation surveys collected along cross section 31. (C) Serial elevation surveys collected along cross section 25

changes at this end of the reach were greater in the interval of time between 2000 and 2002 than between 2002 and 2005. Along cross section 31 (Figure 7B) incision at a distance of 122 m from the head pin and near the right bank of the river at 325 m were the most pronounced. Similar channel incisions can be seen along cross section 25 (Figure 7C) at 220 and 373 m from the head pin.

The model-interpolated sandbar topographies were de-trended for channel slope (Figure 5) and are illustrative of the spatial and temporal evolution of the river bed. In 2000 the large, lobate sandbars are present throughout the reach; deeper areas, while present, took the form of localized scour pools. Subsequent maps reveal that two

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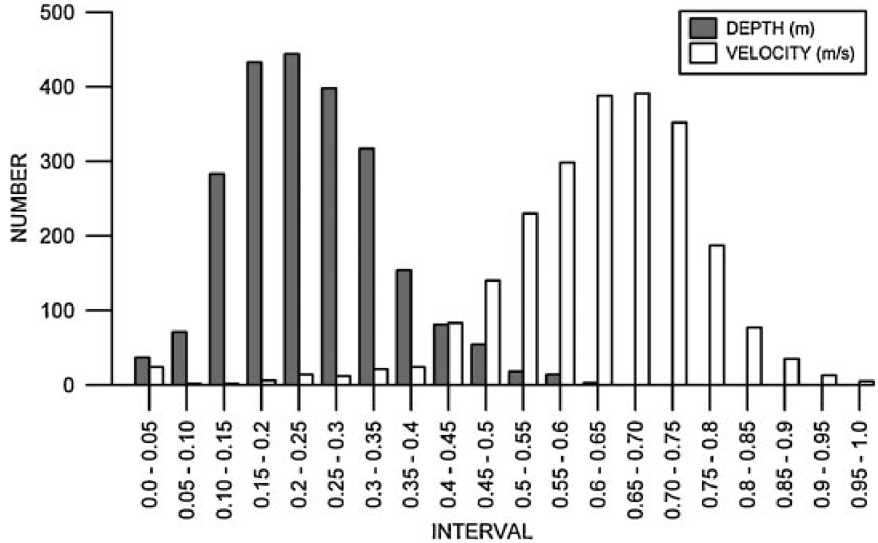

Figure 8. Distribution of depth and velocities computed by the hydraulic model that were utilized by roosting cranes in the Rowe Sanctuary reach on 28 March 2000

principal channels developed at the downstream end of the reach and progressed upstream through time. In 2005 these channels eventually incised into the sandbars at the upstream end of the reach.

Hydraulic modelling

The FaSTMECH model was first run at the highest discharge ($57\,m^3s^{-1}$) and stage (1.01 m) during which observations of roosting cranes were collected, 28 March 2000 (Figure 3C), to determine upper limits of two hydraulic variables (depth and velocity) that were chosen to characterize roost space used by cranes. The coverage containing the depths and velocities generated from the model at this discharge was overlain on the roost area polygons from 28 March 2000 to determine the range in the hydraulic variables in the wetted area used by these cranes (Figure 8). This analysis showed that cranes generally roosted in depths computed by the model less than 0.62 m (mean = 0.25 m, SD = 0.10 m) and in modelled velocities less than $1.07\,ms^{-1}$ (mean = $0.63\,ms^{-1}$, SD = $0.14\,ms^{-1}$). The extreme values in this figure were likely the result of the coarse discretization of the topography in model domain (5×5 m) as well as errors in the image registration process or resolution of the imagery that could have shifted or positioned the roost polygons into deeper and faster portions of the model domain. The upper limit was more conservatively determined to be one standard deviation about the mean of each hydraulic variable. This placed the upper limit of available riverine roost space to be in depths less than 0.35 m and in velocities less than $0.77\,ms^{-1}$.

The upper limit on depth was approximately consistent with roosting observations and by considering anatomical measurements made from sandhill cranes sampled along the central Platte River. Infrared video collected from a river photography blind in the Rowe Sanctuary on the night of 29 March 2000, a night of relatively high stage (Figure 2B) showed cranes roosting in water near their tibio tarsus. The sampled cranes were collected as part of a study which examined their body-fat to determine the health of the cranes (Krapu *et al*., 2005). These data showed that the mean distance from a crane foot to the tibio tarsus or knee joint was approximately 0.24 m for the greater subspecies (*Grus canadensis tabida*) and 0.20 for the lesser subspecies (*Grus canadensis canadensis*) (David Brandt, unpublished data, USGS, Northern Prairie Wildlife Research Center, Jamestown, ND).

The FaSTMECH model also was next used to examine the distribution of wetted nodes and nodes that satisfied the depth and velocity criterion (available habitat) in the channel for two channel topographies, one collected at the beginning of the study in 2000 and the other at the end of the study in 2005 (Figure 5A,E). Two discharges were examined for each of the two topographies. First the model was run using the 2000 topography and a discharge of

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$57\,m^3s^{-1}$ to simulate the wetted area shown in Figure 3C. A total of 10 867 nodes were wetted in this simulation; 5665 nodes (52%) satisfied the depth and velocity criterion ($0 < \text{depth} \leq 0.35$ m; $0 < \text{velocity} \leq 0.77\,ms^{-1}$). Of the 2308 nodes that fell within the digitized crane roosting polygons, 1776 nodes (77%) satisfied the criterion. The model was then run using the 2000 topography but with a discharge of $21\,m^3s^{-1}$ to simulate the wetted channel shown in Figure 3D. A total of 8376 nodes were wetted in this simulation; 6301 nodes (75%) satisfied the hydraulic criteria. Of the 2820 nodes that fell within the digitized crane roosting polygons, 2072 nodes (73%) satisfied the depth and velocity criterion. These modelling results indicate that at the higher flow more nodes became wetted. However, the number and percentage of the nodes that were available was greater for the lower flow. In the high-flow simulation, the percentage of nodes meeting the criterion was less than the percentage of nodes that were also used meeting that criterion, suggesting that those criteria are being selected for. At the lower flow the percentage of nodes meeting the criterion that was available were about the same as that used, suggesting that these variables may not be selected for as intensely. This result would be consistent with the low spatial density observed on this night, Figure 6C, indicating that cranes were spread over a greater area at this lower flow than during higher flows in that same year.

When the model was again run with a hypothetical discharge of $21\,m^3s^{-1}$ and the same downstream water-surface elevation but using the 2005 topography, 6530 nodes were wetted and just 4488 nodes (69%) satisfied the hydraulic criteria. The number of wetted and available nodes was less than that seen in 2000 for the same flow. The distribution of depths and velocities computed by the FaSTMECH model for each channel morphology at a flow of $21\,m^3s^{-1}$ is shown in Figure 9A,B. These plots present the number of nodes in each depth and velocity interval. The hydraulic simulation using the 2000 channel morphology produced more nodes in the depth range between 0 and 0.35 m than the 2005 morphology with the same flow. The number of nodes in the velocity range between 0 and $0.77\,ms^{-1}$ was also much larger for the 2000 channel morphology than for the 2005 morphology. As cranes were not present during this hypothetical simulation it was not possible to examine crane use at this flow. However, a final model run was made using the 2005 topography and a discharge of $14\,m^3s^{-1}$ to simulate the wetted area shown in Figure 4E. This flow wetted 4803 nodes and 3339 nodes (70%) satisfied the hydraulic criterion. Of the 305 nodes that were occupied by roosting cranes only 172 nodes (56%) satisfied the criterion. This relatively small quantity of nodes used by cranes tended to be located in areas of shallow water adjacent to exposed sandbars. Because of the coarse resolution of the model, simulating the wetted area in these locations proved problematic at this low flow. Many nodes of zero depth were calculated throughout the modelled area, in locations where the thermography would suggest shallow depths were present. However, because the number of nodes used by cranes was small in comparison to the total number in the simulation these nodes were disproportionately affected by the zero depths that were predicted. Spatial densities measured from a flight on a different night in 2005, albeit at a higher stage than that modelled, indicate that the cranes were grouped close together suggesting that habitat quality was reduced. At these lower flows in incised channels hydraulic criterion alone may over-predict the amount of available habitat. This is because as sandbars are exposed, especially along the river bank, cranes may be forced closer to the centre of the channel even though available roosting areas are located along the banks.

DISCUSSION

The average discharges at the Kearney gage for the months of March and April, which overlap the crane migration season, were determined to be 51 and $44\,m^3s^{-1}$, respectively. These computations were made only using years in the interval between 1985 and 2005 where the monthly data for this gage were complete (see monthly statistics for &http://waterdata.usgs.gov/ne/nwis/uv/?site_no=06770200&agency_cd=usgs). In 2000 the average discharge for the month of March was $74\,m^3s^{-1}$, the fourth largest average monthly discharge in this record. Average discharges measured for the month of March in years 2002 through 2005 were each progressively the lowest over this record (28, 20, 19 and $18\,m^3s^{-1}$, respectively). Because our observations were made over a relatively wide range of hydrologic conditions, they are illustrative of the range of hydraulic and geomorphic conditions influencing crane roosting habitat.

After taking into account the statistics of the depths and velocities indicated by the hydraulic model, sandhill cranes were determined to roost in depths less than 0.35 m with velocities less than $0.77\,ms^{-1}$. These upper limits of

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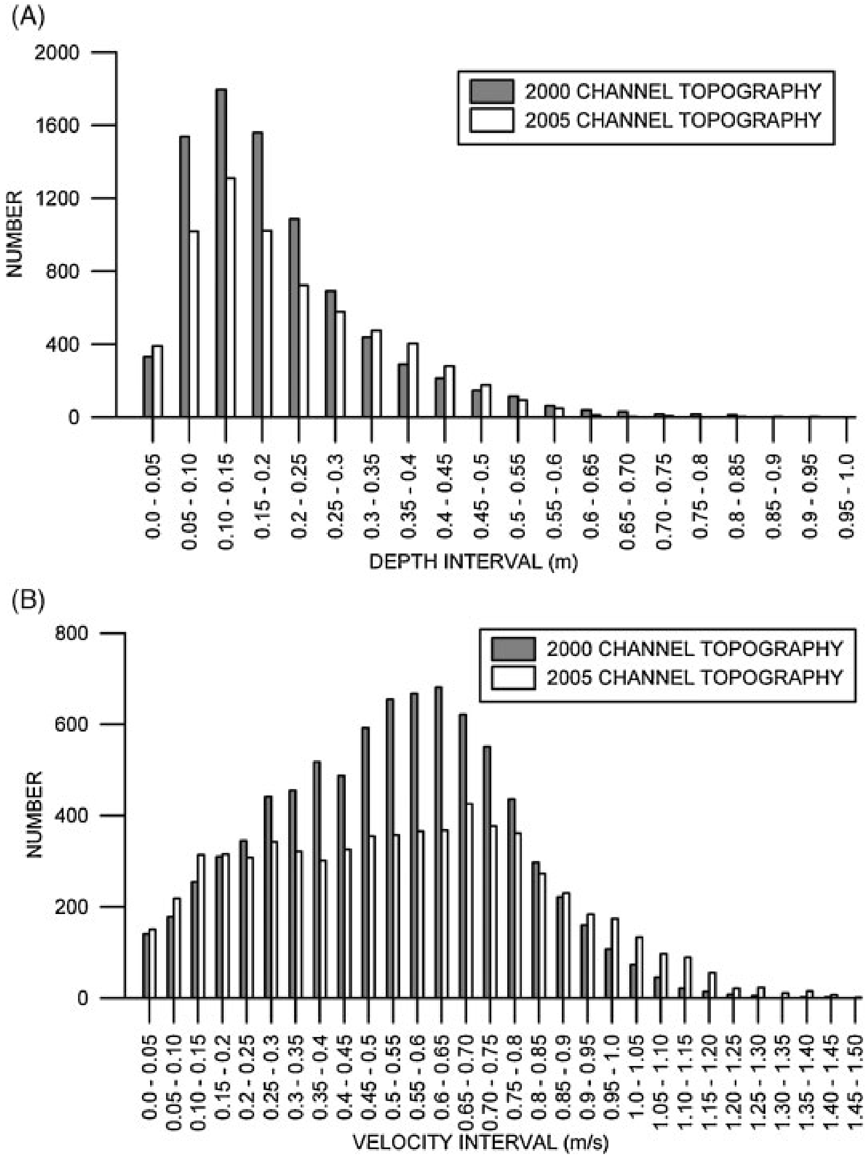

Figure 9. (A) Distributions of depths available in the Rowe Sanctuary reach computed by the hydraulic model for a streamflow of $21\,m^3s^{-1}$ using the topography collected in 2000 and 2005. (B) Distributions of velocities available in the Rowe Sanctuary reach computed by the hydraulic model for a streamflow of $21\,m^3s^{-1}$ using the topography collected in 2000 and 2005

depths and velocities are greater than observations made by previous authors who have investigated the linkage between river flow and roosting habitat for cranes. Latka *et al*. (1986) developed suitability of use indices based on field measurements of water depth, water velocity and distance to large bank or island in conjunction with predawn aerial photography of sandhill cranes. He used these indices to predict the location of cranes in a second location and found a significant correlation between predicted and actual distributions. Most of the cranes in this study were observed in depths ranging from 0 to 0.12 m and velocities ranging from 0 to $0.40\,ms^{-1}$. The influence of water depth on the selection of roost sites for sandhill cranes was also examined by Norling *et al*. (1990). They found that cranes select water depth of 0.01 to 0.13 m and reported that no difference existed in the water depths selected despite changes in water level resulting from a 50% reduction in river flow. While these observations fall within the bounds of our predictions, the observations were made when the river flow was less than the highest discharge observed in 2000 that was used to set the upper limits of our criteria. Other workers have placed the upper limit of

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roosting depth closer to ours. Currier and Ziewitz (1987) put the maximum depth at 0.30 m and Folk and Tacha (1990) observed a maximum of 0.36 m on the North Platte River.

In discussing the observed changes in sandbars in the Platte River, it is helpful to mention that various nomenclatures have been used to characterize and categorize riverine barforms observed in the field and those created in the laboratory. In their observations of braiding in the South Platte and Platte Rivers, Ore (1964) and later Smith (1970) drew a texture distinction between the poorly sorted, coarse-grained longitudinal bars that were depositional features and better-sorted, finer-grained transverse bars. The incision of transverse bars was believed by Smith to be the dominant mechanism of braiding in the Platte River. Crowley (1981) termed the large sandbars he observed along the Platte River downstream from Grand Island, Nebraska 'macroforms'. He reasoned that these macroforms created during high flows belonged to a new class of bedforms based on their wavelength-depth ratios, geometry and the observation that, unlike dunes, flow-separation eddies did not contribute to their formation. However, he believed the presence of vegetated islands and multiple channels made the regular pattern of these macroforms more difficult to distinguish upstream from Grand Island. Fujita (1989) termed the higher mode bars he created in the laboratory 'row bars'. Germanoski and Schumm (1993) drew a mobility-based distinction between those 'linguoid dunes' that were submerged and actively migrating, named after the linguoid bars described by Allen (1968) and Collinson (1970), and 'braid bars' that were stationary and subaerially exposed. They observed in their laboratory channels that braid bars were formed by dissection and accretion of the stalled linguoid dunes and were depositional features that were sculpted by erosion.

The geomorphologic changes observed in the study reach from 2000 to 2005 were consistent with the dissection and stabilization of higher mode sandbars (transverse bars, macroforms, row bars or linguoid bars/dunes). Dissection was initiated by decreasing discharge and associated sediment supply while growth of annual and perennial vegetation likely served to stabilize emergent surfaces in the spring and summer months. The influence of decreasing flows on sandbar dissection and braiding was also observed by Smith (1971) who documented incision of an individual transverse bar in the Platte River during a 5-day period of decreasing discharge. In observations of linguoid bars in the Tana River, Norway, Collinson (1970) noted that during falling stages flow became concentrated between the sandbars cutting shallow channels. Although decreasing sediment supply is associated with decreasing discharge, this variable was examined independently by Germanoski and Schumm (1993) who reduced the sediment supplied to their laboratory channel at constant discharge and produced a degrading condition that had the effect of causing smaller bars to coalesce, decreasing the braiding index. Gran and Paola (2001) demonstrated in their flume experiments that stabilizing bars with increasing vegetation density reduced the number of active channels and the braiding index and increased the topographic relief of the channels. The interrelated variables influencing the channelization in the Rowe Sanctuary were not easily separated. However, in these field observations, stabilization effects from older growth perennial vegetation were not present. This leads us to conclude that decreasing flows and sediment supply and perhaps the presence of annual vegetation and young perennial saplings were responsible for the channelization observed.

Model predictions and remote sensing observations suggest that similar discharges do not produce identical distributions of wetted area and depth and velocities for different sandbar morphologies. Perhaps more importantly for those concerned with habitat management, higher flows would be required in the incised morphology to approach the quantity of available riverine roosting area produced from the lobate morphology. Furthermore, even if the amount of useable habitat is equalled it may be located in the incised channels that may not be used by cranes because of their close proximity to the river banks. These observations should also be of interest to managers developing streamflow targets for channel maintenance. It would require less streamflow to overtop lobate sandbars than it would to inundate the same area for the incised morphology.

A number of years of historically low streamflows incised sandbars in the Rowe Sanctuary reach produced more exposed sandbar area, and altered the distribution and area of wetted channel available for roosting cranes. Thus, the distribution of available roosting habitat is influenced by both the instantaneous flow as well as the flow history, which served to shape the sandbars in the channel. The morphological changes occurred despite the fact that aggressive management of perennial in-channel vegetation was in place throughout the study. Because of this management only the growth of annual vegetation and perennial saplings on sandbars during the spring and summer months contributed to the stabilization of exposed sandbar surfaces. Measurement of cross-section changes in the Rowe Sanctuary following a short duration (3 h) peak flow of 90 m^3s^{-1} at Kearney from a local

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precipitation event in mid-May 2005 (Figure 2A) indicated that the channel morphology was not markedly altered from the morphology measured in March 2005 (Figure 5E,F). However, this peak flow was less than historical peak flows that generally occurred in spring and summer from snowmelt from the Rocky Mountains. Historical peak flows measured at Overton, Nebraska from 1915 to 1942, which was the year that Kingsley Dam on the upstream North Platte River started impounding water, ranged from 66 to 1065 m^3s^{-1} with an average value of 406 m^3s^{-1}. In contrast, the peak flows during the study ranged from 57 to 127 m^3s^{-1} with an average value of 79 m^3s^{-1} (see peak streamflow for &http://waterdata.usgs.gov/ne/nwis/uv/?site_no=06768000&agency_cd=usgs).

Streamflows of the magnitude and duration to reshape sandbars in the channel were not observed during the study. Upstream releases of water directed towards improving habitat conditions in the central Platte River need to be designed to be of sufficient magnitude and duration to mobilize the sandbars in the channel and alter the distribution of wetted channel area. If these releases are made at a time of the year when significant annual vegetation establishment has occurred on sandbars or on surfaces that have developed perennial vegetation, mobilization of these sandbars will be made more difficult and there is the potential for further channelization. Similarly, flow releases of insufficient magnitude or duration would first fill the incised channels and would either fail to or only partially inundate higher surfaces.

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